AD 665301

RDTR No. 105
January 1968

VOLUME I OF II

25 MILLION CANDLE CAST FLARE, DIAMETER AND BINDER STUDY
(Summary Report June 66 to June 67)

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Prepared under MIPR PG-6-58 for the Illumination Branch, Targets and Scorers Division, Air Force Armament Laboratory, Eglin Air Force Base, Florida

84

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This report was reviewed for adequacy and technical accuracy by Mr. W. S. Cronk, Mr. Larry Moran, and Captain Gene Holder, Eglin Air Force Base and Mr. Clarence Gilliam, NAD Crane.

Submitted by:

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TABLE OF CONTENTS FOR VOLUME I

TABLE OF CONTENTS FOR VOLUME II

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The feasibility of making an illuminating candle which produces a luminous intensity of 25 million candles is demonstrated. The goal is achieved by igniting all surfaces of a star shaped cavity which is formed through the center of the candle. Two horizontally opposed flames are generated by this candle.

The relationship between candle diameter and the ability of that candle to generate light efficiently is reported. This study includes data for both pressed and cast candles and shows the effect of different binder types. A general degradation of efficiency is observed as the cast candle diameter increases from 4 inches to 24 inches. The pressed candle series shows a maximum near the 4 inch diameter with degradation to either side.

Silicone, epoxy-polyglycol, polyester, polysulfide, and various combinations of these binders are described as they are used to make candles for the diameter study and the 25 million candle flare. A study of flare compositions consisting of magnesium and sodium perchlorate, the latter being partially dissolved in various methacrylate monomers is reported. A limited environmental program for a 4.5 inch diameter candle cast in an aluminum candle case and the development of a liner system for that candle is described. A polyester-epoxy

binder is used successfully to make a cast candle whose luminous efficiency is comparable to a candle made by the conventional pressed method.

Flame orientation and flame size effects are described. Contrary to common opinion, it is shown that a small flame size rather than a large flame from a given candle diameter is associated with candles which produce light with high efficiency. The binder is shown to be a major factor in the generation of various flame sizes and thus strongly influences the candle efficiency.

INTRODUCTION

This exploratory development program was conducted between June 1966 and June 1967 for the Air Force Armament Laboratory, Eglin Air Force Base, Florida, under MIPR-PG-6-58. The main objectives of the program were twofold. One goal was to demonstrate the feasibility of making an illuminating candle which has a luminous intensity of 25 million candles. This is a five-fold increase over the intensity delivered by the BRITEYE candle. The second goal was to conduct a study of the relationships between the diameter of a candle and the efficiency of light production from that candle. Both goals were attained during the contract period.

To assist the reader, the report is divided into four parts. Part I deals with the 25 million candle flare, Part II with the diameter studies, Part III with binder studies, and Part IV with flame orientation and flame size effects. Although the report is divided for convenience, it is noteworthy that all phases of this work are interrelated; that is, information generated in any one part is also utilized in the other phases in

an effort to extract the maximum amount of data from a minimum amount of work and hardware expenditure. With these remarks, the reader is encouraged to view this work as an integrated program instead of four distinct tasks.

The report is bound in two volumes. The main body of the report is in Volume I. The Appendices are in Volume II. A Table of Contents, Abstract, and Introduction for the entire report has been inserted at the beginning of each volume for convenience.

PART I

25 MILLION CANDLE FLARE

Purpose

The purpose of this report is to describe the exploratory development effort which led to the fabrication of an illuminating flare candle which generates a luminous intensity of 25 million candles.

Chronological Approach

During the manufacture of a conventional illuminating flare, the composition is normally consolidated into the flare container at a pressure near ten thousand psi. Furthermore, when it is necessary to make flares with a large cross-sectional area, extremely large presses are required in order to achieve the 10,000 psi consolidation force. Thus, the size of the candle that can be made is often limited by the size of press which is available. For example, a press of about 200 tons is required to consolidate the composition into an 8-inch diameter flare. Larger flares require correspondingly larger presses.

Since the consolidation operation becomes more complex as the size of the equipment increases, it becomes increasingly attractive from an economical standpoint to eliminate the consolidation operation. This can be achieved if the composition is cast into the candle container instead of pressed. The casting method is the technique chosen to make candles in this program. Appendix I gives additional information about the flare composition and the flare manufacturing technique. Generally, the composition will

not flow and therefore is tamped at pressures near 50 psi. For purposes of this report, the process of tamping and later polymerization of the composition is what is known as casting a flare candle.

In an effort to attain outputs of 25 million candles, flares were made in the normal solid cylindrical shape. It was estimated that flares of sufficient diameter and size could be made which would provide the required 25 million candle output. When these flares were tested, they burned in cigarette fashion. Two important characteristics of the process became evident: First, the luminous intensity output was found to degrade as the diameter of the candle increased. At the start of this program this degradation function was not defined. A separate part of the program entitled "Diameter Studies" was started in the effort to define the function. That work is described separately. The other benefit that came from this phase of the work was the development of the techniques required to process the composition. During the manufacture of the solid candles, various mixing, tamping, and casting techniques were tried. In addition, different composition formulas were used. All of this led to the preparation of candles which performed reliably and predictably.

During the early phases it was learned that about five pounds of composition needed to be burned per second in order to generate luminous intensities of 25 million candles. This in turn requires the burning of large composition surface areas in order to obtain the desired output. Since this would require candles of extremely

large diameters, if they were made as a solid cylinder, another approach was taken. Candles were made which had a star-shaped cavity as shown in Figure 1. The purpose of the star cavity was to present a larger surface area for burning. This idea is based on computations developed for the burning of propellant grains of various star configurations. Representative computations are provided in Appendix II.

Candles with the single star cavity exhibited one undesirable trait: the combustion within the cavity and subsequent exhaust of the flame gases through the cavity opening provided a propulsion effect. This made the candle difficult to control during test. Secondly, candles with a shallow single-star cavity did not provide the necessary output. Accordingly, candles with deeper cavities were tested in the next phase.

When it was found necessary to make candles with deep cavities in order to burn five pounds of composition per second, it was decided to make two additional changes: first, instead of making the candle with a single star cavity, candles were made with a star shaped cavity completely through the center of the candle as shown in Figures 2 and 3. Clearly then, when the candle is ignited, the flame can exit from both ends of the candle. This will give equal but opposing forces thereby eliminating the propulsion effect described earlier. Secondly, it was decided to suspend the candle in a horizontal position which causes the flames to develop horizontal to the surface of the ground. In this manner, a larger projected cross-sectional surface area of the flame is

CANDLE
WITH STAR SHAPED CAVITY

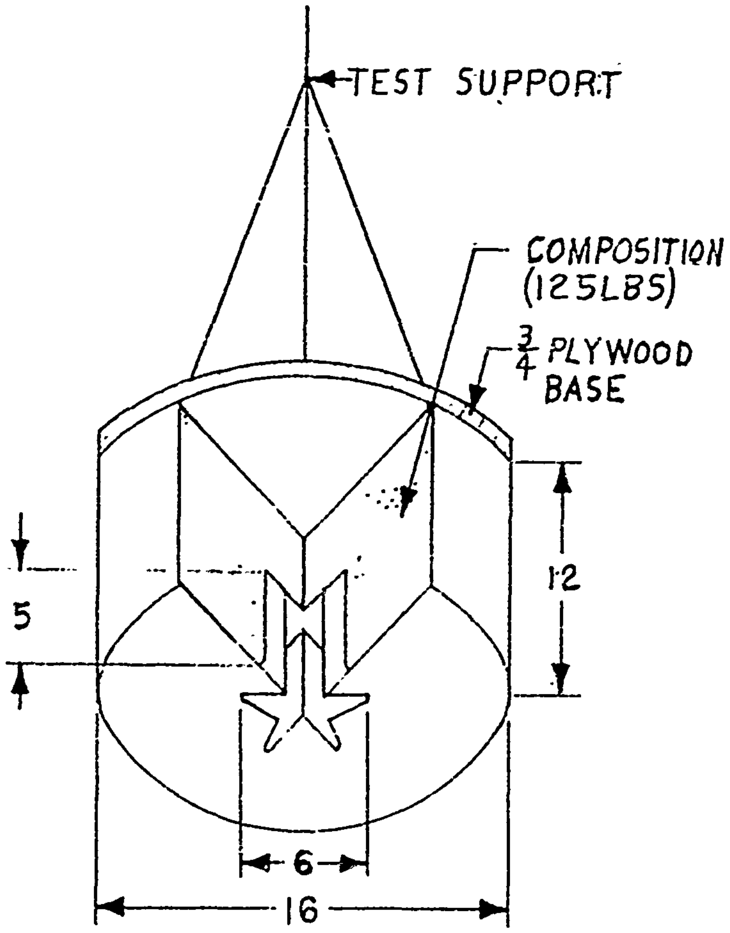

Figure 1: Sketch of single-star-cavity candle
This design was used for candles MAPI 300, 342 and 343.

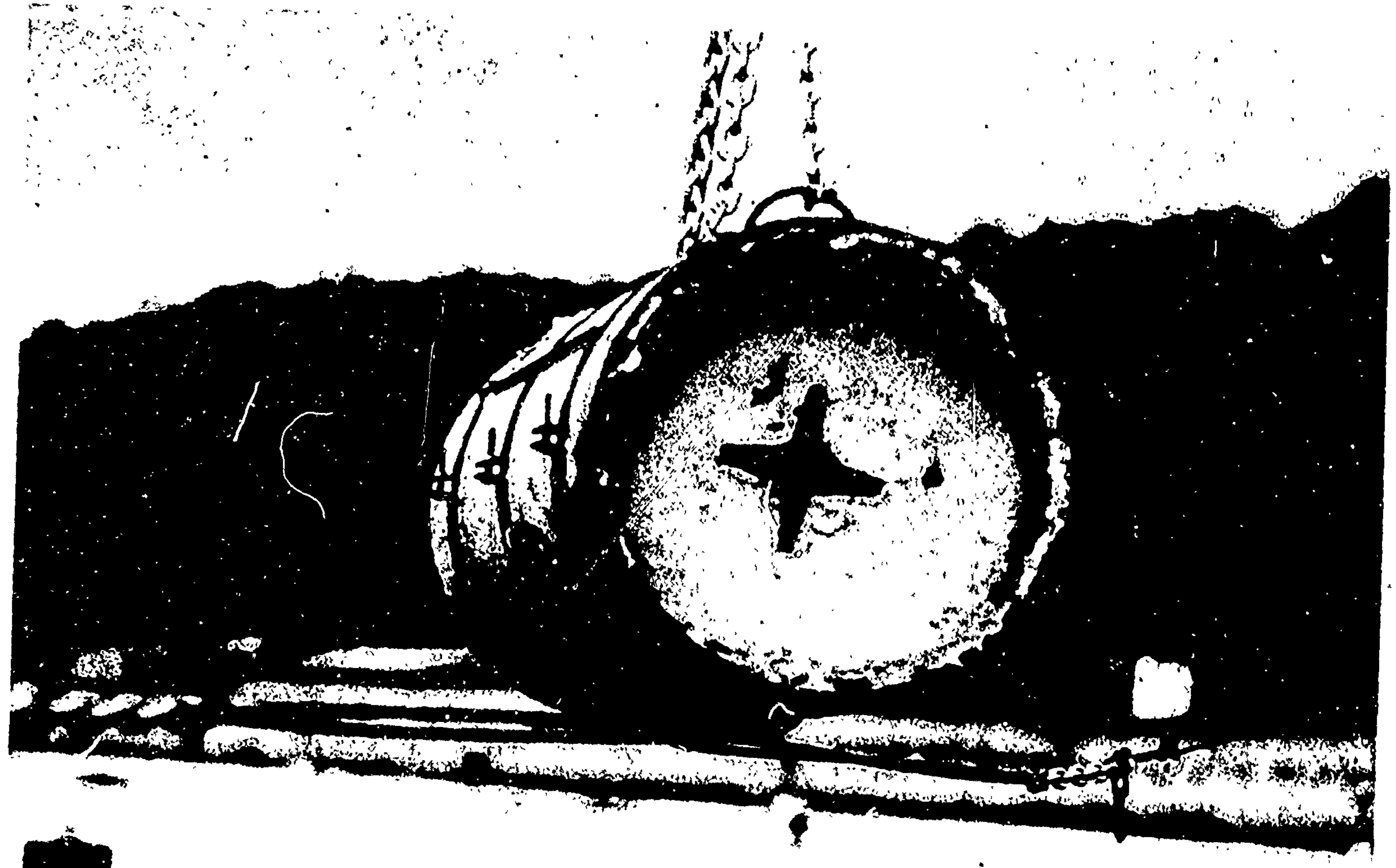

Figure 2: View of suspended double-star cavity 16 inch diameter candle

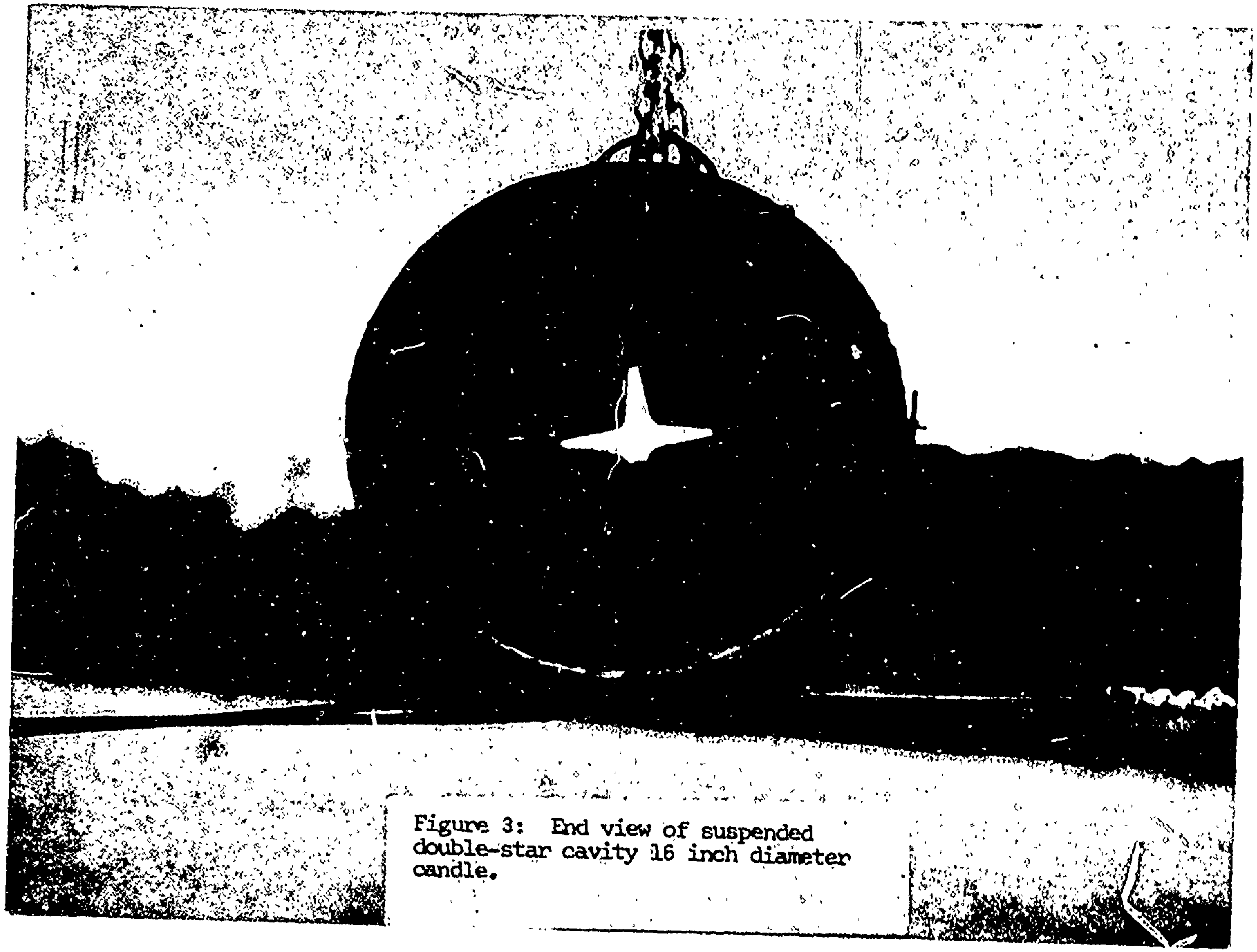

Figure 3: End view of suspended double-star cavity 16 inch diameter candle.

presented to the ground surface. This double star candle design was used successfully to generate the required luminous intensity of 25 million candles.

Experimental

All of the candles were tested at the MAPI site. In general, the MAPI site may be described as a polar arrangement of about 62 photocells on the ground each of which views the candle suspended about 80 feet in the air. Figure 4 is a schematic of the photocell layout. The cells are arranged such that the flare is viewed from all aspects. The cells numbered DS-1 through DS-8 are not located on the same scale in Figure 4 as the remaining 56 cells. Cells numbered DS-1, DS-3, DS-5, and DS-7 are 300 feet away from the flare whereas cells DS-2, DS-4, DS-6, and DS-8 are 200 feet away from the flare. These eight cells were added to the MAPI system during this program. The cells were placed at the greater distances in order that the entire flame could be viewed by the cells. Additional details about the MAPI site may be found in references (1), (2), (3), and (4).

Tables I and II are summary sheets for single and double star cast flares. Additional test data about each of these flares is provided in Appendix III, which is the numerical analysis of the data recorded during the test.

Discussion

The 25 million candle output requirement was demonstrated by both candles MAPI No. 426 and MAPI No. 463. In each case from Table II is is apparent that about five pounds a second of compo-

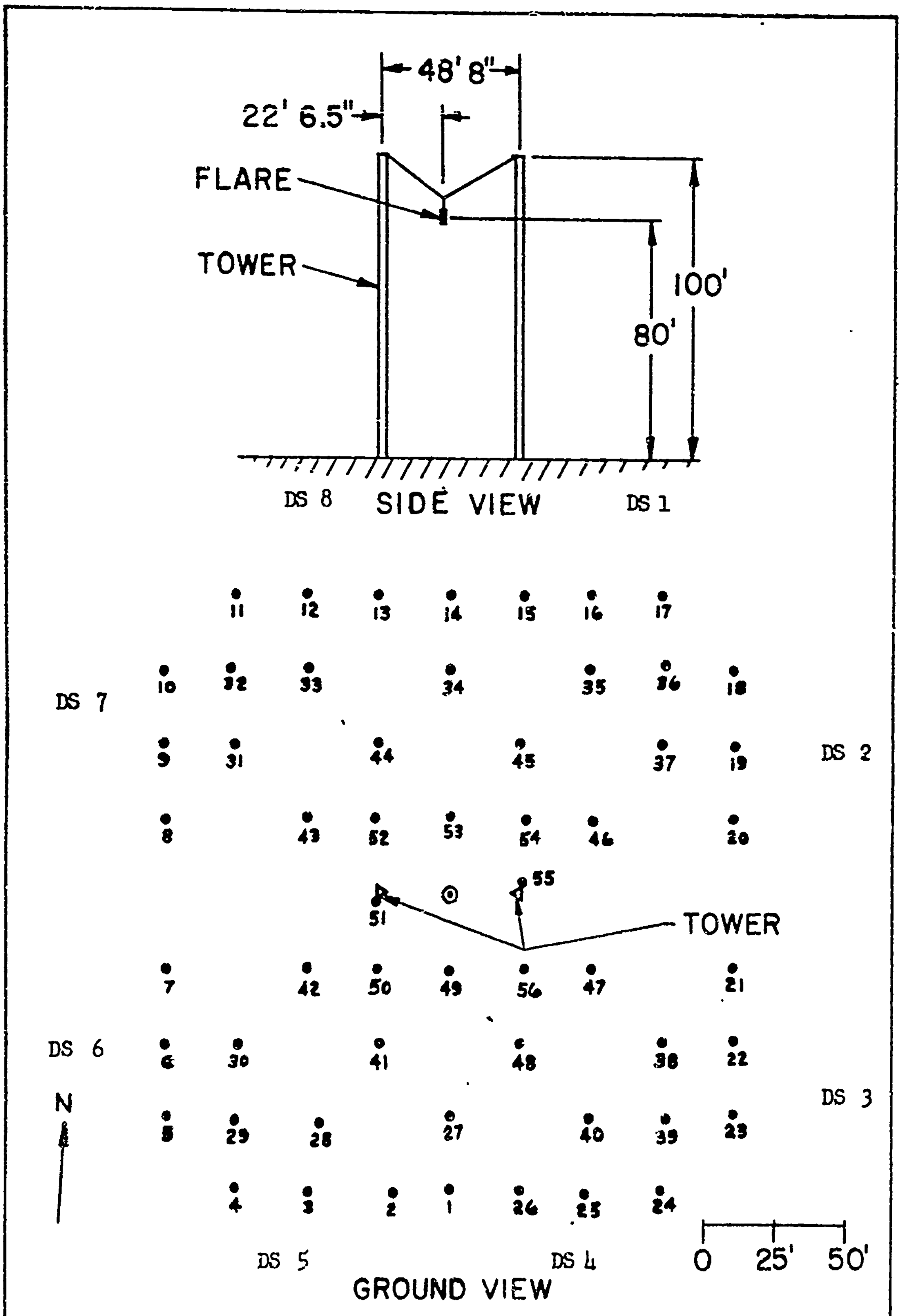

Figure 4: Plot plan of photocells showing their location in relation to the test towers.

TABLE I

16.0" DIAMETER SINGLE-STAR FLARE

12 September

MAPI Test No.	300	342	343
Magnesium %	56.8	58.4	58.4
(granulation)	(15)	(15)	(17)
Sodium Nitrate%	28.8	28.8	28.8
(particle size)	(150µ)	(150µ)	(150µ)
Binder* %			
Silicone	14.4	12.8	12.8
Luminous Intensity ($x10^6$cd)	11.4	14.0	9.4
Burning Time (sec)	62	47	69.4
Efficiency ($x10^3 \frac{cd\text{-}sec}{g}$)	12.8	11.0	11.9
Burning Rate (in/sec)	0.05	0.16	0.07
Burning Rate (sec/in)	12.5	9.3	13.0
Burning Rate ($x10^3$g/sec)	0.3	1.2	0.8
Composition Weight ($x10^3$g)	56.7	56.7	56.7

* Silicone formula: Sylgard 182 plus curing agent.

TABLE II

16.0" DIAMETER DOUBLE-STAR CAST FLARES — 12 September 1967

MAPI Test No.	394	426	427	463	464	556
Magnesium %	56.8	56.8	56.8	56.8	56.0	35.1
(granulation)	(17)	(15)	(17)	(17)	(15)	(15)
Sodium Nitrate %	28.8	28.8	28.8	28.8	29.0	49.9
(particle size)	(150μ)	(150μ)	(150μ)	(150μ)	(150μ)	(150μ)
Aluminum Chaff %					1.0	1.0
Binder* %						
Silicone	14.4	14.4	14.4	14.4		
Epoxy-Polyglycol					14.0	14.0
Luminous Intensity ($x10^6$cd)	15.1	25.0	18.0	24.3	13.6	6.5
Burning Time (sec)	37	36	48	49	93	93
Efficiency ($x10^3$ $\frac{cd\text{-}sec}{g}$)	10.1	11.1	10.7	9.8	15.5	7.4
Burning Rate (in/sec)	0.13	0.13	0.10	0.10	0.05	0.05
Burning Rate (sec/in)	7.6	7.2	9.7	9.9	18.7	18.7
Burning Rate ($x10^3$g/sec)	1.5	2.2	1.6	2.4	.87	.87
Composition Weight ($x10^3$g)	56.7	81.6	81.6	122.5	81.7	81.7

* Silicone formula: Sylgard 182 mix.
Epoxy-Polyglycol formula: 62% QX 3812 and 38% DER 732.

sition is burned. Also, the tables show that efficiencies in (cd-sec)/g generally range from ten to twelve thousand. This is only about one-fourth of the efficiency achieved when compared to the standard pressed illuminating composition in a four-inch size. Although these efficiencies are low, it is suggested that they might be improved considerably by utilizing more efficient binder systems or by improvement of the manufacturing techniques. In any event, the binder systems and techniques used did provide a means for the preparation of a candle whose output achieved the required 25 million candle luminous intensity.

Two other interesting observations were made. First, it was noticed that the luminous intensity was a direct function of the amount of flare composition burned per unit time. This relationship is shown in Figure 5. Secondly, a relationship between flame surface area and luminous intensity of the flare may be a direct function of the surface area of the flame projected toward the photocells as shown in Figure 6. It is suggested that this relationship is valid for a given composition formula in combination with particular candle geometry. On the other hand, these characteris-- tics should not be interpreted that the flame is solely a surface emitter. Additional discussion and data regarding this point may be found in Part IV.

Two different binder systems are shown in Table II as being utilized to make the double star candles. The silicon resin system has the characteristic of burning much faster than does

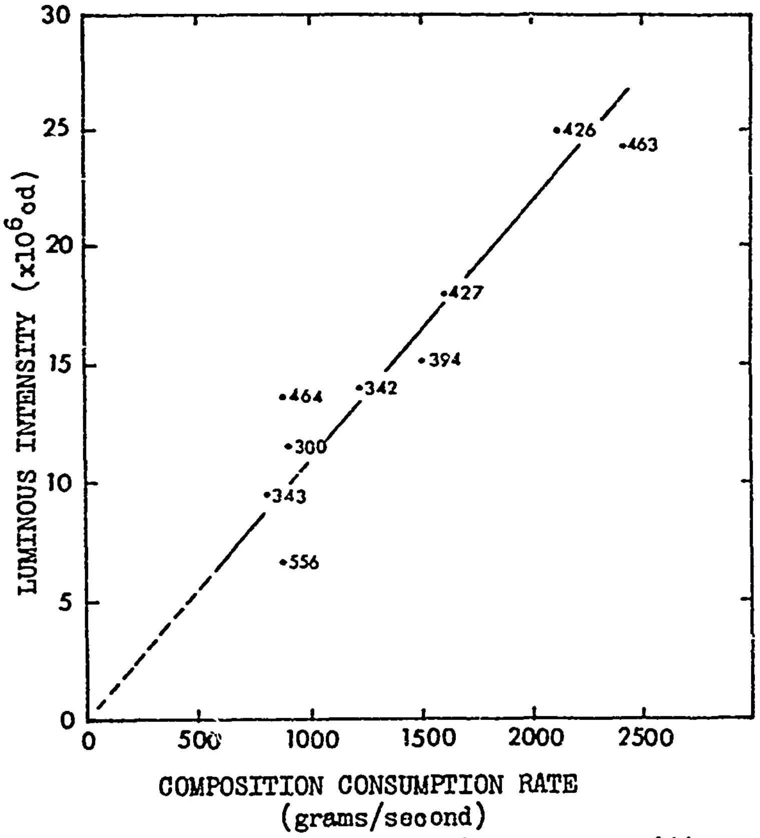

Figure 5: Luminous intensity vs composition consumption rate. Shows that at given efficiency, about 5 pounds of flare composition needs to be burned per second in order to achieve an intensity of 25 million candles. Numbers on data points are the candle MAPI test numbers.

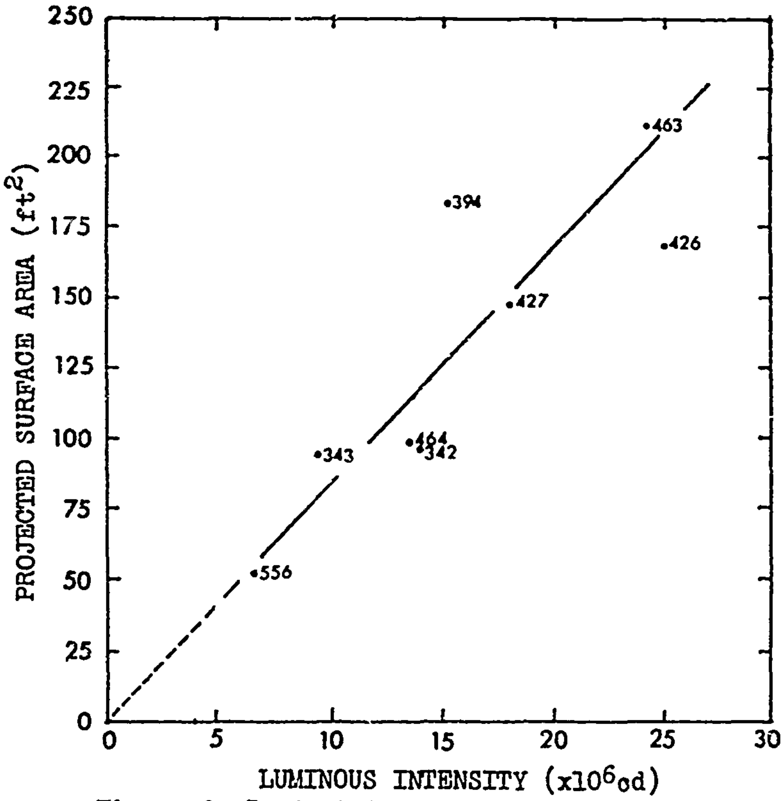

Figure 6: Projected surface area of the flame vs the luminous intensity. Shows that candles with either a single or double star shaped cavity and made with either an epoxy-polyglycol or silicone binder all exhibit the same behavior (linear to first approximation). Numbers on data points are the candle MAPI test numbers.

the epoxy-polyglycol system for comparable composition formulas. Both of these resin systems have the very desirable characteristic of a very low exotherm during the polymerization reaction. Generally, their pot life is about eight hours which permits adequate time for the casting process. After the candle is cast, it is placed in an oven at around 150-170°F for 24 hours or more to cause the cure. During this curing period, the exotherm is almost unnoticeable. This characteristic is extremely important from a safety standpoint, in particular when it is necessary to cure large section candles. Because the exotherm is extremely low, there is no danger of exceeding the decomposition temperature of any of the flare ingredients.

Conclusion

It has been demonstrated that a luminous intensity of 25 million candles can be delivered by a pyrotechnic illuminating flare. The information gathered during this phase of the program suggests that considerable improvement can be made by increasing the efficiency of this system. It is suggested that the efficiency increase can be achieved through the use of more efficient binder systems or through improvement of the processing and manufacturing techniques.

PART II
DIAMETER STUDIES

Purpose

The purpose of this work was to determine the relationship between the luminous efficiency of a flare and the flare's diameter. In this program, the flares were all end-burning, solid units, fabricated in paper cases.

Chronological Approach

The experiment was originally designed to include only flares that were consolidated at around 8000-9000 psi. Three composition formulas were selected for comparison at varying candle diameters. The diameters chosen were 1.76 inches, 2.66 inches, 4.25 inches, and 7.35 inches. The latter two sizes correspond to the MK 24 parachute flare and the BRITEYE flare, respectively. All of these flares were to contain 5% polyester (Laminac) binder and magnesium at 55%, 62% and 70%. The remainder of each formula consisted of sodium nitrate of an average particle size of 30 microns.

About this time, a cast flare program was being conducted concurrent with the binder study. Thus, it was convenient to extend the binder study to include a cast series of candles. This segment of the program included cast flares which ranged from 4.25 inches to 24 inches in diameter. Because four different binder materials were conveniently available, it was decided to make a diameter series with each of the four binder types.

One of the binder types chosen was a polyester (Laminac). This system was chosen to permit direct comparison to the pressed polyester series. Other systems chosen were the polysulfide, silicone, and epoxy resins. These resins were chosen to represent a wide diversity of types. For example, included are carbon backbone materials as well as sulfur and silicon backbone materials. The carbon types include both the polyester and the epoxy systems.

At this point it was learned that certain binder systems would perform reasonably well when consolidated at reduced pressures. For example, consolidation pressures of 2,000 to 3,000 psi were used instead of the

normal 8,000 to 9,000 psi. In a manner of speaking, these units, pressed at medium pressure are a cross between high pressure consolidation and casting. For this reason, this group of low pressure pressed units is called the "hybrid" series.

Units of the hybrid series were made in the 2.66 inch-, 4.25 inch-, and 7.35 inch-diameter sizes. The consolidation pressure was chosen such that the 7.35 inch-diameter size could be consolidated using a 60-ton press instead of the 200-ton press. The latter capacity is needed when consolidation pressures near 10,000 psi are required.

In summary then, the diameter study consists of a series of candles pressed at the 8,000 to 9,000 psi level, the hybrid series consolidated at 2,000 to 3,000 psi, and the cast series made with a tamping pressure of about 50 to 60 psi. The range of sizes of the candle is from 1.76 inches diameter to 24 inches diameter. All of the candles were made in the solid cylindrical configuration. That shape burns in cigarette fashion.

Experimental

Figure 7 shows the matrix of the diameter study for the candles consolidated at about 8,000 psi using a polyester as a binder. Figure 8 shows the matrix of the diameter study for the hybrid and cast series. The numbers in the matrices identify the candle.

The data collected from these test flares have been summarized in tabular form. The test data for each of the candles in the pressed and hybrid series of the diameter study may be found in Appendix IV. Appendix V includes all of the summarized data for the cast series of flares.

The tremendous amount of data collected makes it difficult to comprehend. Accordingly, a series of graphs were made to assist the reader in visualizing the results of this study. A graph was made showing each of the three pressed series and the hybrid series. Another graph was made for each of the binder types in the cast series. Finally, a graph which is a composite of all of the cast series was prepared so that these curves could be compared directly. All of these graphs are included in Appendix VI. Finally, in an effort to

Composition Formula *

DIAMETER	A	B	C
1.76 inch	T-499, 502 T-2624, 2625 T-3375, 3376 T-3377, 3378	T-500, 503 T-2626, 2627 T-3379, 3380 T-3381, 3382	T-501, 504 T-2628, 2629 T-3383, 3384 T-3385, 3386
2.66 inch	MAPI 484, 493 MAPI 538, 547 MAPI 623 thru 626 T-11836 thru 11850 MAPI 645 thru 648	MAPI 487 MAPI 496 MAPI 541 MAPI 550	MAPI 490 MAPI 499 MAPI 544 MAPI 553
4.25 inch	MAPI 485 MAPI 494 MAPI 539 MAPI 548	MAPI 488 MAPI 497 MAPI 542 MAPI 551	MAPI 491 MAPI 500 MAPI 545 MAPI 554
7.35 inch	MAPI 486 MAPI 495 MAPI 540 MAPI 549	MAPI 489 MAPI 498 MAPI 543 MAPI 552	MAPI 492 MAPI 501 MAPI 546 MAPI 555

*Ingredient	Group A	Group B	Group C
Magnesium (granulation 18)	55%	62%	70%
Sodium nitrate (30μ)	40%	33%	25%
Polyester binder	5%	5%	5%

Figure 7: Matrix showing candles by diameter and formula which made up the pressed series in the diameter study.

FLARE TYPE

DIAMETER (INCHES)	PRESSED POLYESTER	HYBRID EPOXY	CAST SILICONE	CAST EPOXY	CAST POLYESTER	CAST POLYSULFIDE
1.76	SEE FIGURE 7					
2.66		609,614 619,640				
4.25		610,615 620,722	506 521	579,587 588	578,585 586	649,650 651
7.35		611,616,621 641,642,643 644	465 505	469 470		
8.0				577,584 607	576 583	652 653
12.0			504,507 523	605 606		
16.0			203,299,370 371,393,424 467	383,392 575	574	419,421 422,423
20.0			503	604		
24.0			502	603		

Figure 8: Matrix showing candles by diameter and type which made up the diameter study. Numbers are MAPI test numbers.

present all of the data from this study in composite form, all of the graphs were put together on a common scale. These curves are shown in Figure 9. In Figure 9 one can find all of the information generated from the diameter studies presented graphically for direct comparison of all test series in relation to each other.

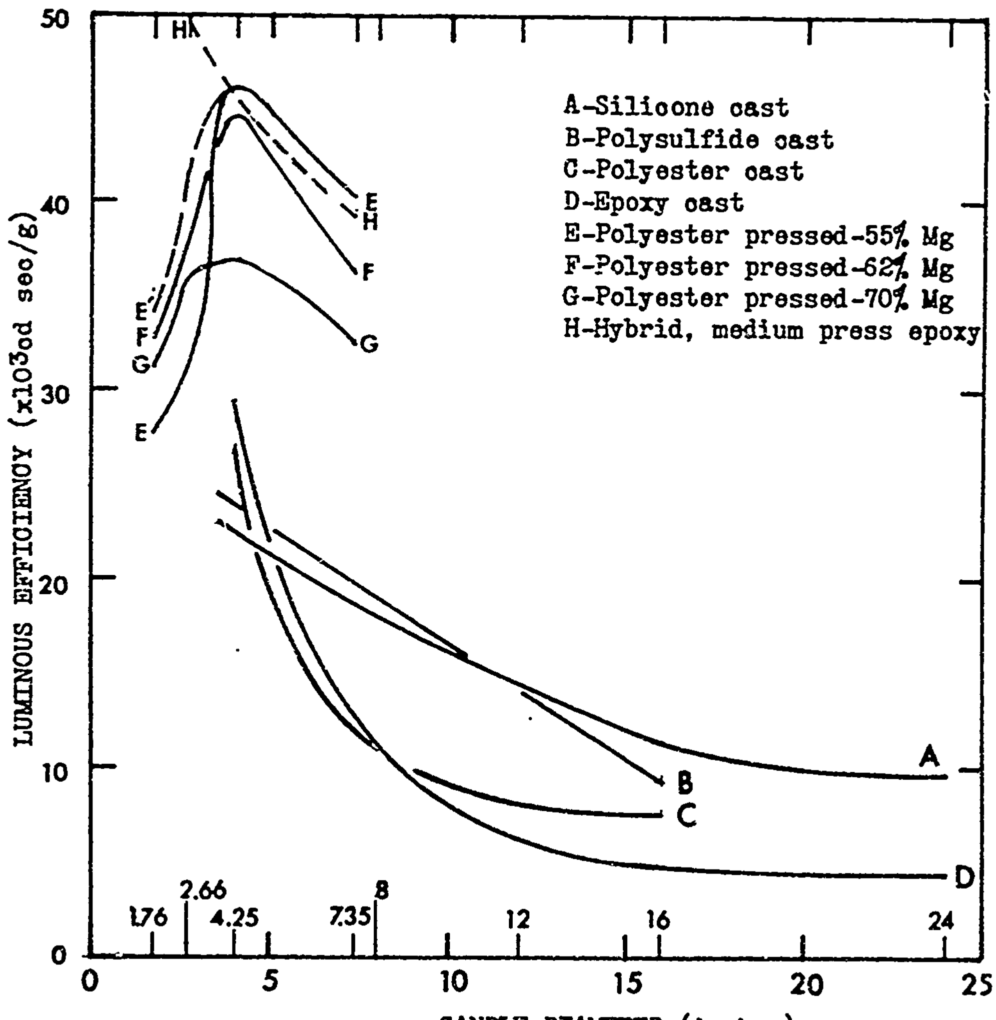

Figure 9: Luminous efficiency vs candle diameter. Shows behavior for end burning solid cylindrical candles with paper candle case all burned in vertical position on MAPI site with flame pointed downward.

Discussion

The data from the diameter studies is shown in Figure 9. The graphical presentation of the data disclosed some unexpected information which is part of the discussion which follows.

Let us first take a look at the pressed series of candles. This series is represented by curves E, F, and G. Generally, curves E, F, and G peak in the neighborhood of 4.25-inch diameter. The degradation of efficiency on the small diameter side of the peak seems to be more severe than it is on the large diameter side. On the other hand, this observation may be the result of experimental error. Another observation can be made as follows: Curve E, which represents the formula containing 55% magnesium, generally is more efficient than curve F, which is made up of a formula containing 62% magnesium. Both of these formulas are more efficient than group G, which contains 70% magnesium. It is therefore concluded that not only is the efficiency influenced by the candle diameter, but also the efficiency is a function of the magnesium to sodium nitrate ratio.

The pressed series in this diameter study were all made with the same binder; that is, a polyester. The three parts of the pressed series differ in the ratio of magnesium to sodium nitrate present in the formula. In another study described in reference 5, the silicone resin system was pressed in 4.25 inch diameter candles in a manner similar to the polyester candles in the pressed series of this study. The silicone resin was found to cause a gross degradation of the luminous intensity from these flares. With the use of this additional limited information to support the statement, it is concluded that the efficiency in the pressed series is not only a function of the candle diameter and the magnesium to sodium nitrate ratio as previously mentioned but also is a function of the binder type.

Curve E needs a little additional discussion. As presented, curve E intersects curves F and G on the small diameter side of the peak. This result was unexpected. Furthermore, the validity of this curve on the small diameter side of the peak is questioned. It is suggested that the curve should follow the dashed line represented by curve E'. The difference between curve E' and curve E on the small diameter side of the peak is believed to be due to instrumental error.

It is known that experimental data gathered in the photometric tunnel at Crane for a given candle is not numerically identical to experimental data from a similar candle tested at the MAPI site at Crane. It is from this situation that part of the difference discussed in the preceding paragraph may have originated. An additional source of error may have been introduced at the 2.66 inch diameter because these candles generate insufficient intensity to cause the photocells at the MAPI site to respond in their most accurate region. Nevertheless, an effort was made to present all of the data in Figure 9 on a MAPI equivalent basis. In an effort to obtain a conversion factor, 2.66 inch diameter candles, MAPI 623 through 626, and 645 through 648 were tested on MAPI, and candles T-11838 through T-11950 were tested in the photometric tunnel. A comparison of the data for these 2.66 inch diameter candles shows that the tunnel values multiplied by 80.2% yield the MAPI values.

Based on these tests, this conversion factor was used to convert data for all of the 2.66 inch- and 1.76 inch-diameter sizes which were burned in the tunnel to the MAPI equivalent. It should be emphasized once

again that although a conversion factor was obtained in this manner, the 2.66 inch-diameter samples tested at MAPI did not cause the photocells to respond in a desirable region and therefore it is not surprising that an error may have been introduced such that we observe curve E as intersecting with curves F and G instead of following the dotted line as E'. The latter would have been more reasonable.

Curve H on Figure 9 represents the hybrid series. Once again, the 2.66 inch-diameter size data is questioned in the light of the discussion in the preceding paragraph. On the other hand, because the deviation is gross, there is that possibility that an extremely high efficiency does, in fact, occur at the 2.66 inch-diameter.

The shape of the hybrid curve between 4.25 inch and 7.35 inch diameters can be compared directly to curve E. In this region, the two curves respond similarly. The fact that the hybrid series performs at almost equal efficiency to the series represented by curve E is most encouraging. This is particularly noteworthy inasmuch as no effort was made to optimize these compositions. It is suggested that if the composition were optimized, the hybrid series could be made to perform even more efficiently. In that eventuality it would then be feasible to convert production

to the low pressure consolidation method. This in turn would mean that the BRITEYE candle, for example, could be pressed with a 60 ton press instead of the 200 ton press now required. Production economies from this change would accrue immediately due to the tremendously decreased need for capitol investments and tooling.

Curves A, B, C, and D of Figure 9 represent the cast series of the diameter study. Curve A is the silicone resin, curve B is the polysulfide resin, curve C is the polyester resin, and curve D represents the epoxy resin compositions. The polysulfide series and the polyester series represented by curves B and C respectively, were introduced mainly for reference purposes. The processing properties of both of these materials are such that they are not very convenient to utilize. On the other hand, samples were included in order to provide information regarding their response relative to the silicone and epoxy resin types. It is interesting to note that the polysulfide system behaves rather similarly to the silicone system whereas the polyester system behaves more like the epoxy resins.

Both the polyester and the epoxy resins (curves C and D) perform exceedingly well with regard to efficiency at the 4.25 inch size. On the other hand, at the large diameters, these systems do not seem to perform as well as the silicone resin. Thus, it can be concluded that some resin systems are better than others at a given size. The corelary to this is that a binder which is superior at one size will not necessarily be superior at all sizes of candle diameter. This crossover of efficiency was not expected prior to the start of this study. It had been predicted that different binders would have different efficiency levels, but that the curves would run parallel to one another being separated by some constant.

The difference of behavior between the silicone resin and the epoxy resin may be due to one of the intrinsic properties of the resin itself. That is, for a given formula, it has been found that the flare composition made with the epoxy resin burns much slower than the composition made with silicone resin. It was therefore difficult to compare the two binder types directly even though all of the variables were kept constant except that of the burning rate. It is suggested that if a means could be found to make the epoxy composition burn faster without causing some other

interaction to occur, the flare composition made with the epoxy resin may then respond in a manner similar to that of the silicone resin. In an effort to accomplish this, aluminum staples were introduced in the composition to speed up the burning. No success was achieved with this approach nor was any other successful approach found. Until this burning rate difference can be resolved, the conclusions reached from this diameter study must be tempered with the knowledge that these combustion rate differences exist.

Conclusions

Several conclusions can be reached based on the information generated in the pressed series portion of the diameter studies.

a. The luminous efficiency is a function of the candle diameter, the magnesium to sodium nitrate ratio, and the binder type.

b. The luminous efficiency is optimum near the 4.25 inch diameter size, and degrades towards larger and smaller diameters.

These conclusions apply only to candles manufactured in a solid cylindrical shape, to candles which are end-burning and which burn in cigarette fashion, and to candles which are fabricated in paper tubes wherein the composition is pressed near 8000 psi.

If the same stipulations are imposed, except that the consolidation pressure is between 2000 and 3000 psi, we can conclude that the hybrid series responds with almost equal efficiency to the best of the pressed series. It should be noted that between 4- and 7-inch sizes, the difference between curve E and H is not statistically significant. It is suggested that further effort should be directed toward improvement of the hybrid series by optimization of the formula.

In most respects, the cast series of the diameter study exhibited the same characteristics as did the pressed and hybrid series.

a. A luminous intensity degradation is recorded over the entire range of candle diameters (4.25 through 24 inches). This characteristic is common to all of the four binder types.

b. At the 4.25 inch diameter candle size, the polyester and epoxy binders exhibit a higher luminous efficiency than do the silicone and polysulfide binders. At about the 5-inch candle diameter, all of the four binder types exhibit the same luminous efficiency. At candle diameters greater than five inches, the silicone and polysulfide binders show generally a higher efficiency than the epoxy and polyester binders.

c. The study shows that the luminous efficiency is a function of the candle diameter and the binder type. Based on limited additional data, the efficiency may also be a function of the magnesium to sodium nitrate ratio. Qualitatively, it is concluded that some types of binders are preferred at the small sizes, whereas, other types of binders may be preferable at large candle diameters.

Thus, no one binder type may be superior to all others over the entire range of candle sizes.

d. The conclusions are only valid for the specific binders used in this study. These data do not allow the conclusion that, for example, all silicone binders are superior to all epoxy binders. The most important conclusion that arises from these data is that the performance is a strong and variable function of the binder type.

PART III
BINDER STUDIES

Purpose

This segment of the program was conducted in order to locate and evaluate various types of binders which might be suitable for casting illuminating compositions.

Approach

The approach taken to evaluate various types of binders is divided into three parts:

a. First, various epoxy resins and a silicone resin, each of which are commercially available, were evaluated for purposes of casting illuminating compositions.

b. Second, various oxidizing agents were dissolved into monomer systems in an effort to load the binder with oxygen. To the degree that this procedure is successful, the binder system can act not only as a binder but also as a source of oxygen supply. The dual role was expected to permit the formulation of more efficient illuminating compositions.

c. The third part resulted from an unsolicited proposal from the Thiokol Chemical Corporation (TCC). In that proposal, TCC described the preparation of a cast candle whose binder consisted

of a mixture of a polyester and epoxy resins catalyzed by iron linoleate.

Experimental

The casting of flares using the epoxy resin and silicone resin has been described in Parts I and II of this report. Generally, candles prepared with compositions containing the epoxy resin were superior when the candle diameter was relatively small. On the other hand, when candles of large diameter were tested, the silicone resin proved to be superior. In addition, there is a significant intrinsic burning rate difference between the two binder types when incorporated into an illuminating composition. That characteristic was also discussed earlier.

One of the efforts made to increase the burning rate of the epoxy system was the addition of aluminum chaff, sometimes called staples, to the illuminating composition. A similar application is described in reference 6, with regard to the casting of propellant grains. In this program, the burning rate was not increased noticeably by the use of staples. The use of staples is normally effective at binder concentrations in excess of 20%. On the other hand, most of the illuminating compositions studies were prepared with binder concentrations of 14% and less. Accordingly, this may explain why the staples were not effective.

Ordnance Research Incorporated Composition

The segment of the work performed in regard to soluble oxidizers was accomplished by Ordnance Research Incorporated (ORI). That work is described in its entirety in reference 7. The work at ORI started as an extension of the work described in reference 8. Generally, it was found that the methacrylate and acrylate monomers were excellent solvents for inorganic perchlorates of group 2 metals. Instead of using strontium perchlorate, the oxidant described in reference 8, sodium perchlorate was studied by ORI in various acrylate and methacrylate monomers.

During the evaluation of various monomers and the study of the illuminating composition formula, several noticeable characteristics of these materials were uncovered by ORI. Some of these are:

a. Because of superior combustion characteristics, magnesium remains the preferred metal over aluminum.

b. Sodium perchlorate was chosen as the oxidant because of its partial solubility in various monomers. Sodium nitrate would probably have been preferred if it were soluble to the degree that sodium perchlorate was found soluble.

c. Of the available acrylates and methacrylates,

glycidyl methacrylate was found to possess the most suitable combination of properties. Properties considered were: viscosity, vapor pressure, ability to dissolve the perchlorate, exotherm upon polymerization, and combustion characteristics.

d. Magnesium perchlorate and glycidyl methacrylate are hypergolic. Glycidyl acrylate is even more active than is the methacrylate.

e. Traces of acrylic acid or methacrylic acid found in some of the esters studied causes premature polymerization in the presence of magnesium.

f. The polymerization reaction is fairly exothermic. The pot life is rather short.

g. The optimization of the formula led to a 1 to 1 ratio of sodium perchlorate to magnesium and a binder content of about 15 to 16 percent. At this level, utilizing glycidyl methacrylate as the binder, the luminous efficiency of a free-standing grain is about 41,000 candle seconds per gram. The performance of this composition needs to be demonstrated in paper candle cases as well as aluminum candle cases. In addition, the composition needs to be compared to cast epoxy composition as well as the polyester composition developed by Thiokol Chemical Corporation.

The following general procedure is used by ORI to prepare the composition and cast a flare.

a. The proper amount of benzoyl peroxide is added to the measured amount of glycidyl methacrylate.

b. Sometimes Witco Ultrablend No. 11, a wetting agent, is added at this point.

c. Mix the solutions.

d. Add the perchlorate and mix. The duration of mixing should be sufficient to allow for a saturated solution of sodium perchlorate in the monomer to be achieved.

e. Divide the magnesium into three parts and add one part at a time with mixing in between.

f. Finally add the promoter and complete the mixing.

N, N, dimethyl p-toluidine is frequontly used as the promoter.

g. After the mix is completed, the composition is cast by tamping a mold as soon as possible. When polymerization is complete, the grains are subjected to a post-cure temperature of 75°C for 24 hours minimum.

h. The grain is removed from the mold. The exterior surfaces of the grain are inhibited with a polyester resin or similar material. All surfaces

of the grain on which combustion is not desired are inhibited.

i. These grains were normally tested by ORI in a face-up attitude. That is, the grain burns in cigarette fashion, starting from top to bottom, while producing a flame which extends upward from the top face of the candle.

Thiokol Chemical Corporation Composition

Another major contribution in the area of binder studies is that made by the Thiokol Chemical Corporation. The details of the entire program may be found in reference 9. As a result of their unsolicited proposal, the Air Force and the Navy entered into a joint contract with TCC for a limited environmental test program for castable flare compositions in the Mk 24 size. The purpose of this program was twofold: (1) to explore the feasibility of a cast composition and (2) to develop a liner system for use with this cast composition. In this program the candles were cast in aluminum tubes whose exterior dimensions are identical to the exterior dimensions of the Mk 24 paper candle tube (4.625 OD by 18.750 inches long). A liner is placed between the composition and the inside of the tube to provide a measure of insulation as well as to bond the composition to the aluminum case.

The composition formula which resulted from this work, was one which contained 9% of the binder, 61% magnesium and about 30% sodium nitrate. The 9% binder is broken down into about 7.37% of a saturated polyester binder "Foamrez F-17-80" as manufactured by the Witco Chemical Company and 1.53% of an epoxy resin identified as "ERL 0510" as supplied by Union Carbide

Corporation. A small amount of iron linoleate is utilized as a catalyst. See reference 9.

Generally, the ingredients for the TCC composition are processed in a conventional manner. The preblended binder is mixed with the sodium nitrate and magnesium until a homogenous mix is obtained. The composition is then tamped at about 60 psi into its container. It is later cured at a temperature of about 150°F for 60±12 hours.

It should be noted that the sodium nitrate must be processed under low humidity conditions. This is especially important for that fraction of the material which is very finely divided. In addition, high humidity conditions may cause difficulty in the preparation of the liner containing the polyurethane prepolymer. The B. F. Goodrich Chemical Company Product Data Sheet describes the polyurethane (Estane 5720X5) as a polyol reacted with a diisocyanate which is sensitive to water.

The ingredient particle size is also worthy of comment. In the case of both the sodium nitrate and the magnesium, a particle distribution is given in reference 9. Those sizes were chosen in an effort to achieve acceptable performance and high packing properties (density). The sizes should not be interpreted as being the optimum for this application. On the other hand, it is important to notice that judicious selection of the ingredients can contribute

immensely to one's ability to develop a candle whose performance has been optimized.

The liner which is placed between the composition and the aluminum tube consists predominantly of a polyurethane prepolymer impregnated into Kraft paper. Several insulation fillers and curing agents are added to this polymer in order to obtain the desired insulation, adhesive, and processing characteristics. The Kraft paper is coated with the liner mixture and then is cured for a minimum of 24 hours at approximately 150°F. When used, the liner is bonded to the aluminum case with a 2-inch wide strip of the liner mixture on the surface between the outside of the liner and the inside of the aluminum case. Just prior to casting the illuminating composition, the inside of the Kraft paper liner is again coated with the liner mixture and cured for approximately 4 hours at 150°F. The purpose of this operation is to obtain a tacky surface in order to provide a good bond between the liner and the flare composition.

At the base of the candle another liner mixture is used. That mixture consists principally of a carboxyl terminated polybutadiene polymer with some curing agents and fillers. That mixture is placed in the bottom of the aluminum tube as well as to assist in bonding the paper liner to the tube base.

When the case subassembly has been prepared as described, the composition is tamped in place at about 60 psi. When the casting is complete, the unit is placed in the curing oven.

TCC also performed a case bond stress analysis. The grain loading conditions considered were thermal shrinkage from 150°F to -65°F, and an axial acceleration of 25 g. The low temperature was assumed to be a uniform soak condition. The 25 g acceleration was a preliminary estimate of the parachute shock load. Further details of this stress analysis may be found in reference 9.

Of the more than 20 candles fabricated, 11 were tested on the Crane MAPI site. The individual data obtained from this test are tabulated in Table III. As reported in reference 9, several of the candles had been subjected to hot and cold shock, transportation and aircraft vibration sequences, and other environmental and durability tests.

The efficiency of the TCC cast candles is somewhat better than that recorded for standard MK 24 MOD 4 candles. During this contract, it was demonstrated that it is feasible to make an efficient cast illuminating candle in the MK 24 size when the candle case is aluminum. No study was made in regard to the performance of this cast composition in the MK 24 paper candle case.

TABLE III
Mk 24 Size Cast Candle(1)

MAPI	t_b (sec)	Intensity ($x10^6$ cd)	Efficiency ($x10^3$ cd-sec/g)	Burn Rate (in/sec)
627(3)	176	1.63	42.59	.0938
628	206	1.86	52.08	.0879
629	208	1.87	52.54	.0870
630	190	1.87	51.06	.0905
631	193	1.68	47.56	.0881
632	185	1.82	47.89	.0935
633	194	1.77	48.50	.0887
634	198	1.66	46.39	.0879
635	209	1.69	46.35	.0861
636	95(2)	2.97	35.75	.1916
637	180	1.88	46.77	.0961
639(3)	179	1.50	39.86	.0922

(1) Test on NAD Crane MAPI site, 6 July 1967. Intensity and burning times are from the computer printouts.

(2) Burned through side of case.

(3) These Mk 24 Mod 4 units had a composition length of 16.5 inches and a composition weight of 14.85 lbs.

Accordingly it is difficult to make direct comparisons between the TCC composition cast in aluminum tubes and the MK 24 composition pressed in paper tubes. However, the formula developed by TCC appears to have great potential.

PART IV
FLAME ORIENTATION AND FLAME SIZE EFFECTS

Purpose

During Parts I, II and III of the program, photographs were taken of the flame. This photographic data was analyzed and compared to the flare performance. The purpose of this segment of the report is to present that data.

Approach

During the diameter studies and binder studies, photographs were taken of the flame. The procedure for taking the photographs was to collect the image of the flame with a parabolic mirror and project it onto an easel. The image on the easel was photographed. In addition, the easel was calibrated for size in order to provide a means for estimating the size of the flame. Later the projected surface area of the flame was estimated by use of a planimeter. The surface area estimates were each plotted against the average luminous intensity of the parent flame. The resulting curve which gives an estimate of light output per flame surface area will hereafter be called an effective brightness curve. This phrase is used knowing that the data does not represent true flame brightness and that an exact brightness value cannot be obtained from the data collected in this program.

Discussion

It has long been known that the luminous intensity of a flame is some function of its size. The exact relationship, however, was not known. In the case of a flame resulting from the combustion of a given ratio of sodium nitrate to magnesium, it was usually postulated that the effective brightness is a constant. This can lead to the misleading conclusion that the luminous radiation can be increased simply by increasing the surface area of the flame. It is true enough that more light will usually be recorded from a flame whose size has been made significantly larger. On the other hand, it does not necessarily follow that this is the most effective approach to the problem of increasing the amount of light produced nor should it be assumed that the relationship is linear and independent of variables such as the binder type, the binder concentration, the ratio of fuel to oxidant, or the pressure used to make the candle.

As will be evident from the discussions which follow, a mere change in the binder type often results in a gross change in the effective flame surface area even when there is no change in the amount of binder in the formula or in the metal to oxidant ratio. Furthermore, the effective brightness function often is nonlinear as the flame size becomes larger even though all of the

flames in the series resulted from a composition which was not varied in regard to binder type or metal to oxidant ratio. To get larger flames in this situation, the candle diameter was increased.

The apparent nonlinearity needs to be discussed further. The nonlinearity always seems to progress toward a luminous intensity increase per unit of flame projected surface (increased effective brightness) as the size of the flame increases. This behavior might suggest that the flames become progressively more optically thick as they increase in size. Also, the recorded luminous efficiency of the flare in cd-sec/g is usually better when, from a given diameter candle, the effective brightness is high.

For purposes of clarity, the information will be presented in several segments. First, we will discuss that information which resulted directly from the diameter studies using only the polyester binder. These studies represent candles that were pressed at around 8000 psi. Next, we will present information concerning candles which were also pressed at around 8000 psi, but whose flare compositions contained either an epoxy binder or a silicone binder. And finally, information will be presented regarding the hybrid candles which were pressed at between 2000 psi and 3000 psi. All of this information about pressed candles will be compared

to candles prepared by the casting method.

In the cast series, data will be presented which compares candles containing polyester, epoxy and silicone binders. In addition, information will be presented to compare the flames from the candles cast in aluminum tubes by the Thiokol Chemical Corporation (TCC) to other cast candles. With the exception of the TCC series, all the test units whether pressed or cast were in a paper candle case.

Individual graphs of effective brightness of the flame are provided in Appendix VII for candles which were pressed at around 8000 psi with polyester, silicone, and epoxy binders. In addition, that Appendix contains the plot of the hybrid series which was pressed at around 2000 to 3000 psi.

Let us first consider data from the series consisting only of candles pressed with the polyester (Laminac) binder. The candles were made in two groups. One group was made in January, and the other group was made in March. Each group was made up of candles containing three different flare composition formulas. The formulas differ in respect to the magnesium to sodium nitrate ratio.

It was found that the January group showed generally a lower luminous efficiency than did the March group. The cause of this difference between two sup-

posedly identical groups has not been identified. Secondly, the candles containing 55% magnesium were always the most efficient within the group whereas the candles containing 70% magnesium were the least efficient in each group. As one can see in Figures 10 and 11, there is a remarkable correlation between luminous efficiency and effective brightness of the flame. Except for curve Q, which one would expect to be below curve P, the effective brightness graphs for each group form an order which is relatable to the magnesium percentage in the flare formula. This order is also the same as the order that luminous efficiency takes for the same units.

In Figure 10, for example, the 55% magnesium line (curve Q) represents an efficiency of about 42,000 cd-sec/g. The 62% magnesium line (curve P) represents an efficiency of about 40,000 cd-sec/g. Since both formulas produced about the same efficiency, this may explain why the curves are so near to one another. Also, because of experimental uncertainties, curve Q is found above curve P instead of below where one might have expected it to be. The curve with the least light output per flame surface (effective brightness) is represented by the 70% magnesium line whose efficiency is around 34,000 cd-sec/g. Thus, in this group of flares as well as the group shown in Figure 11, low efficiency

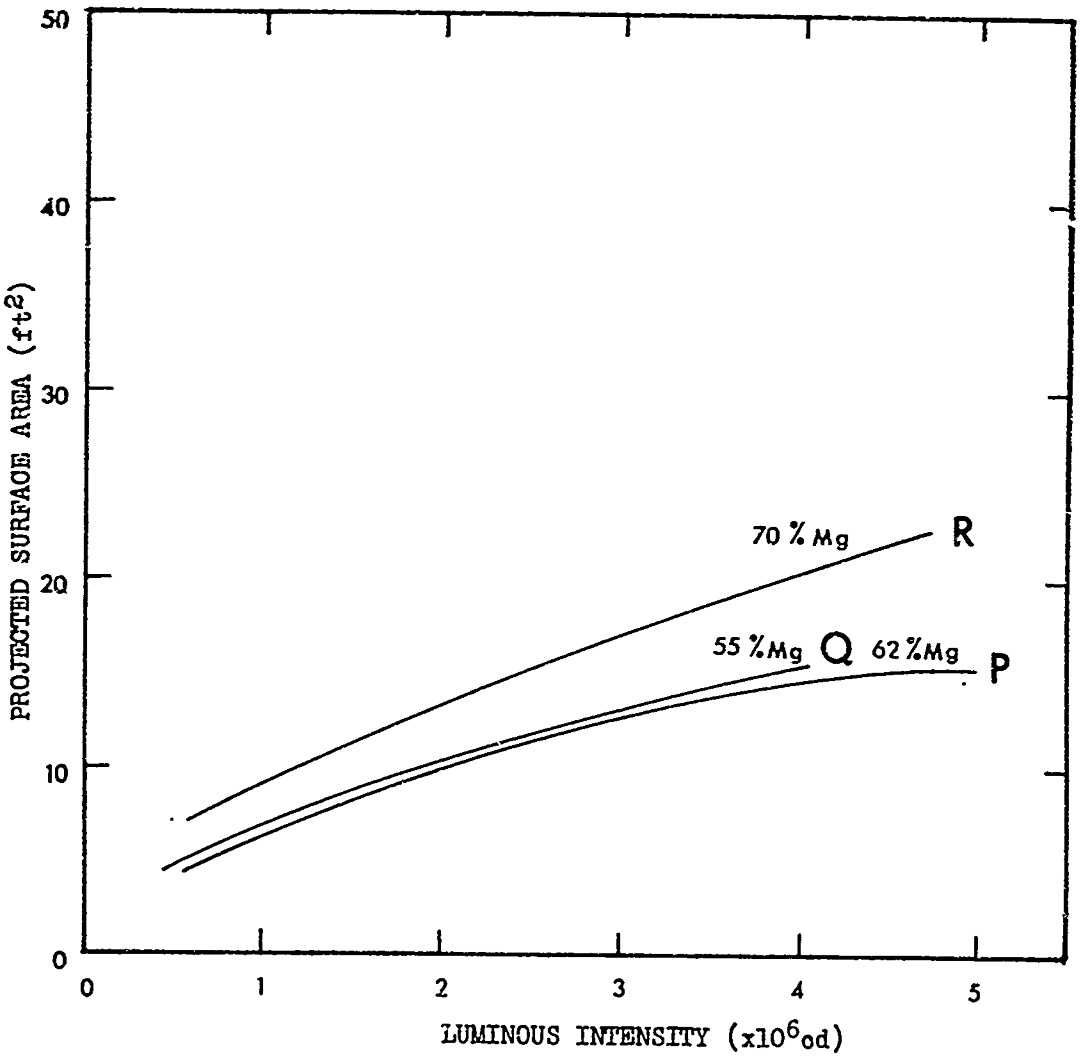

Figure 10: Effective Brightness Curves. Projected surface area of the flame vs luminous intensity for 2.66, 4.25, and 7.35 inch diameter candles pressed with 5% polyester binder and tested in January 67. High luminous efficiency (55% Mg) corresponds to high effective flame brightness (curve Q).

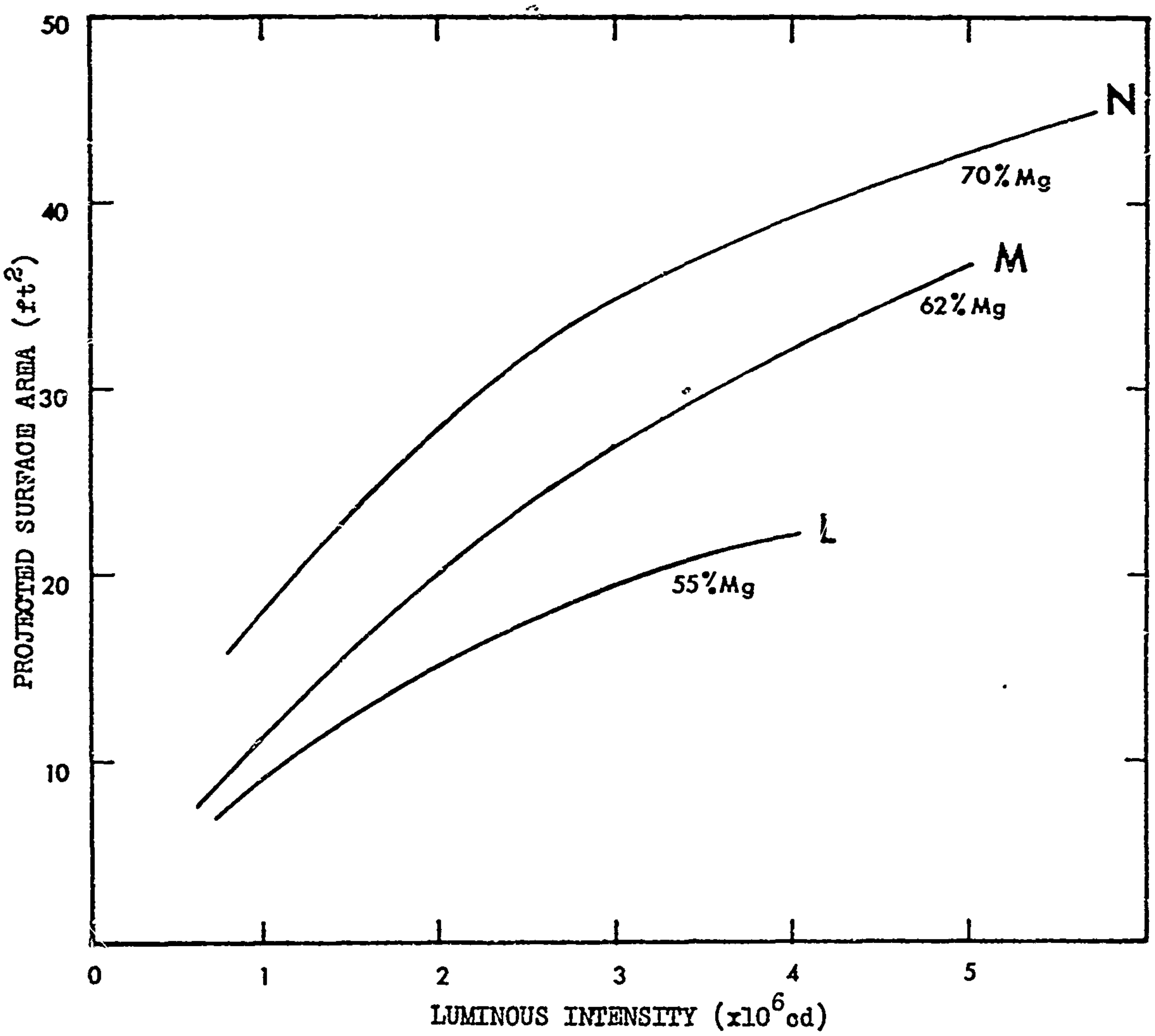

Figure 11: Effective Brightness Curves. Projected surface area of the flame vs luminous intensity for candles pressed with 5% polyester binder and tested in March 67. High luminous efficiency (55% Mg) corresponds to high effective flame brightness (curve L).

is associated with low effective brightness and high efficiency is associated with high effective brightness. Seemingly, for a given diameter candle, the flame with the smaller surface area is usually the more efficient.

By comparing the effective brightness curves in Figure 10 to Figure 11 and in view of the preceding discussion, one would conclude that all of the groups in Figure 10 should be more efficient than the groups in Figure 11 because the curves in Figure 10 all show a higher effective brightness for the flame. This is not the case. Generally, the groups in Figure 11 are more efficient. To find an explanation for what appears to be an inconsistency, one must utilize burning rate data tabulated for these candles in Appendix IV.

Comparison of the burning rate data shows a trend which explains why, on a diameter to diameter basis, all candles in Figure 11 produce a larger flame than candles in Figure 10. Generally, the Figure 11 candles burned significantly faster. Logically, this should produce more flame gases per unit time; hence a larger flame. Clearly then, burning rate is also a factor which must be dealt with when one attempts to draw conclusions from the effective brightness data.

Having completed the discussion of the effective brightness curves for the pressed candles with poly-

ester binder, we will now compare the best of that series (curve L) to pressed candles with other binders. For these comparisons, one should refer to Figure 12.

In Figure 12, the L curve is the same as the L curve in Figure 11 and is the effective brightness curve for candles pressed with a polyester binder. Candles pressed with epoxy binder are represented by the K curve and those with a silicone binder by the J curve. The hybrid series is shown by the H curve.

Comparison of the curves in Figure 12 leads to the same general conclusions reached during discussion of the data in Figure 11. Candles pressed at about 8000 psi with polyester binder (curve L) form a curve which is remarkably similar to the K curve which represents candles pressed at about 8000 psi with an epoxy binder. Each of these series have about the same luminous efficiency. Although the hybrid candles also had about the same luminous efficiency, the effective brightness curve H for these units behaves somewhat differently. It is suggested that this difference may be associated with the lower consolidation pressure (about 3000 psi) at which these units were made.

The J curve for candles pressed with a binder containing silicon is included for reference. Candles from this series show an efficiency about 25% less than the other series. The J curve may be unreliable because

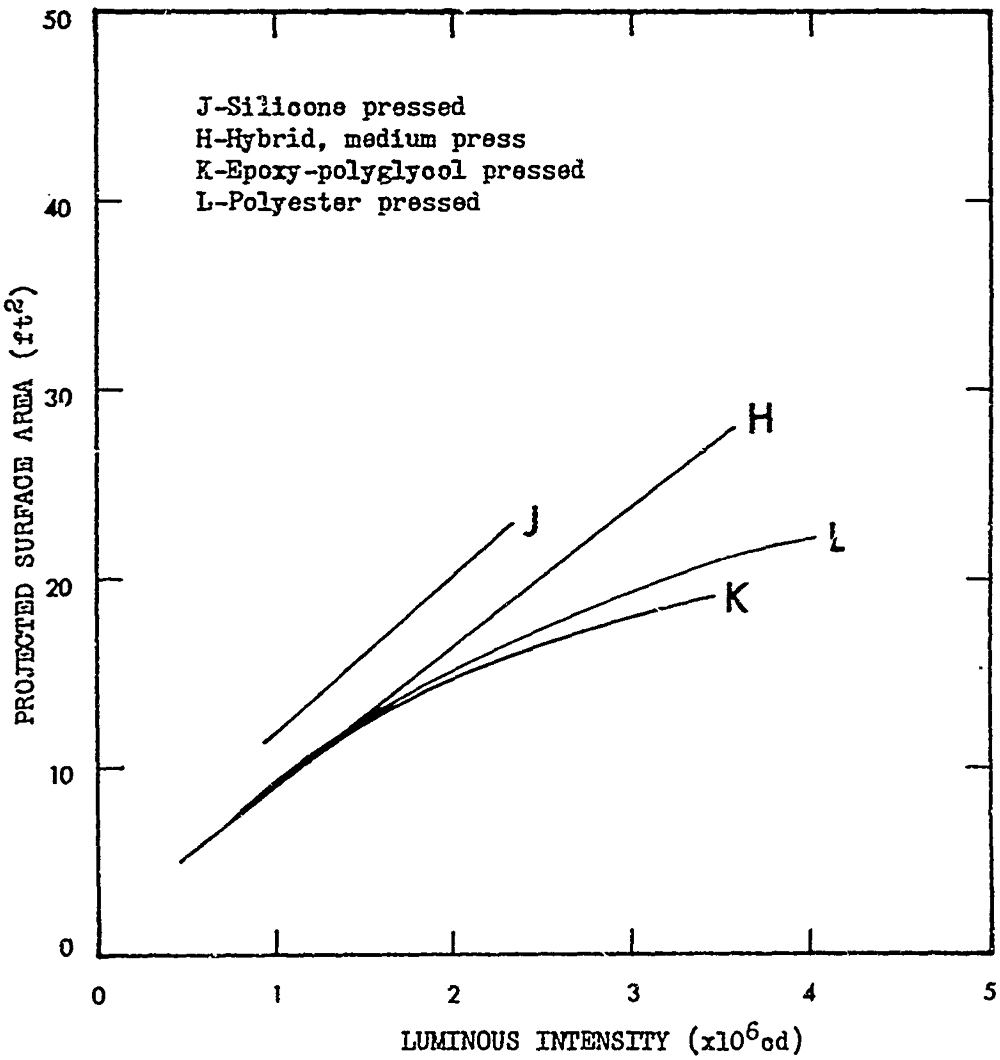

Figure 12: Effective Brightness Curves. Projected surface area of the flame vs luminous intensity for candles pressed with various binder types. High luminous efficiency (epoxy and polyester) correspond to high effective flame brightness (curve K and L).

it is drawn using only 5 data points.

Next let us compare the effective brightness curves for the cast series by binder type. See Figure 13. Individual curves have been plotted for each binder type. These may be found in Appendix VIII. We observe that curves V and W exhibit a low effective flame brightness. For these units cast with a polyester or epoxy binder, this corresponds to the low efficiency as shown earlier in Figure 9. The most efficient of the three binder types was the silicone resin which also has a high effective flame brightness (curve S). A fourth curve has been included for reference. That curve (T) contains information gathered from the TCC flares (see Part III) prepared with a polyester-epoxy binder in an aluminum tube. These candles, which were very efficient, also exhibit a high effective flame brightness. Except to generally show that high efficiency is relatable to a high effective brightness, one should not attempt to draw additional conclusions from the TCC flare data because of the different case material used in these candles.

The conclusion reached earlier for the pressed candles also seems to be valid for the cast candles. Once again, a high effective brightness is relatable to high luminous efficiency.

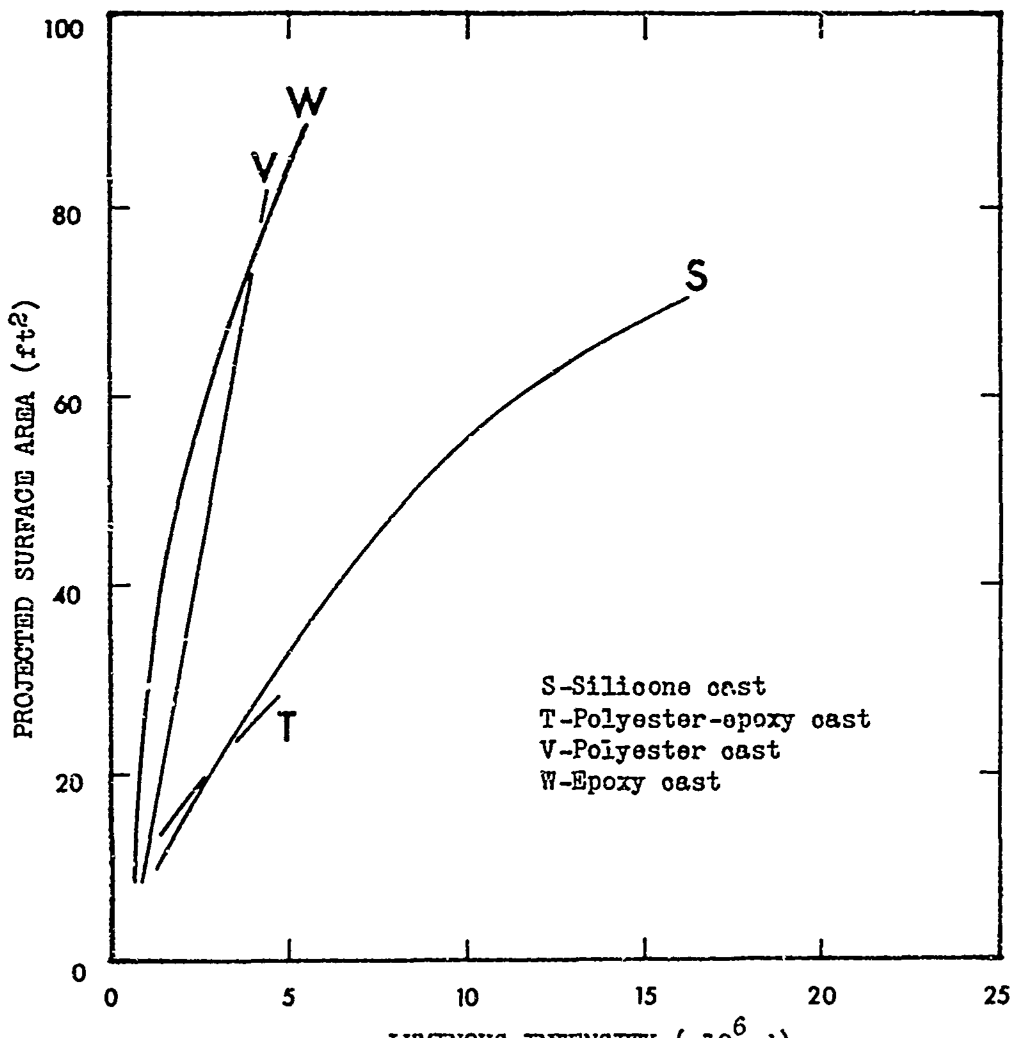

Figure 13: Effective Brightness Curves. Projected surface area of the flame vs luminous intensity for candles cast with various binder types. High luminous efficiency (silicone and polyester-epoxy) correspond to high effective flame brightness (curves S and T).

Figure 14 was prepared to show the way that the flame projected surface area varies between the epoxy (curve Y) and silicone (curve X) binders from a given candle size. Generally, from a given candle diameter, the epoxy binder generated a flame with a larger projected surface area. This observation corresponds well with the postulate advanced earlier that a small flame from a given candle diameter is associated with a high luminous efficiency.

Most of the discussion to this point involves only solid end burning candles. In contrast to these we next will discuss data from candles which have a star cavity in the center. See Part I of this report for additional details about star cavity flares.

A flame effective brightness plot had previously been presented as Figure 6. The function is linear over an extremely wide range of projected surface area and luminous intensity. The linearity is particularly remarkable when one realizes that this graph consists of both epoxy and silicone binder types used to make flares with single-star-blind-holed cavities, as well as flares with a star cavity completely through the unit. The flames from the single star units were displayed vertically and downward, whereas the flames from the double star unit were displayed horizontally opposed. Finally, the luminous intensity ranges from 5 million

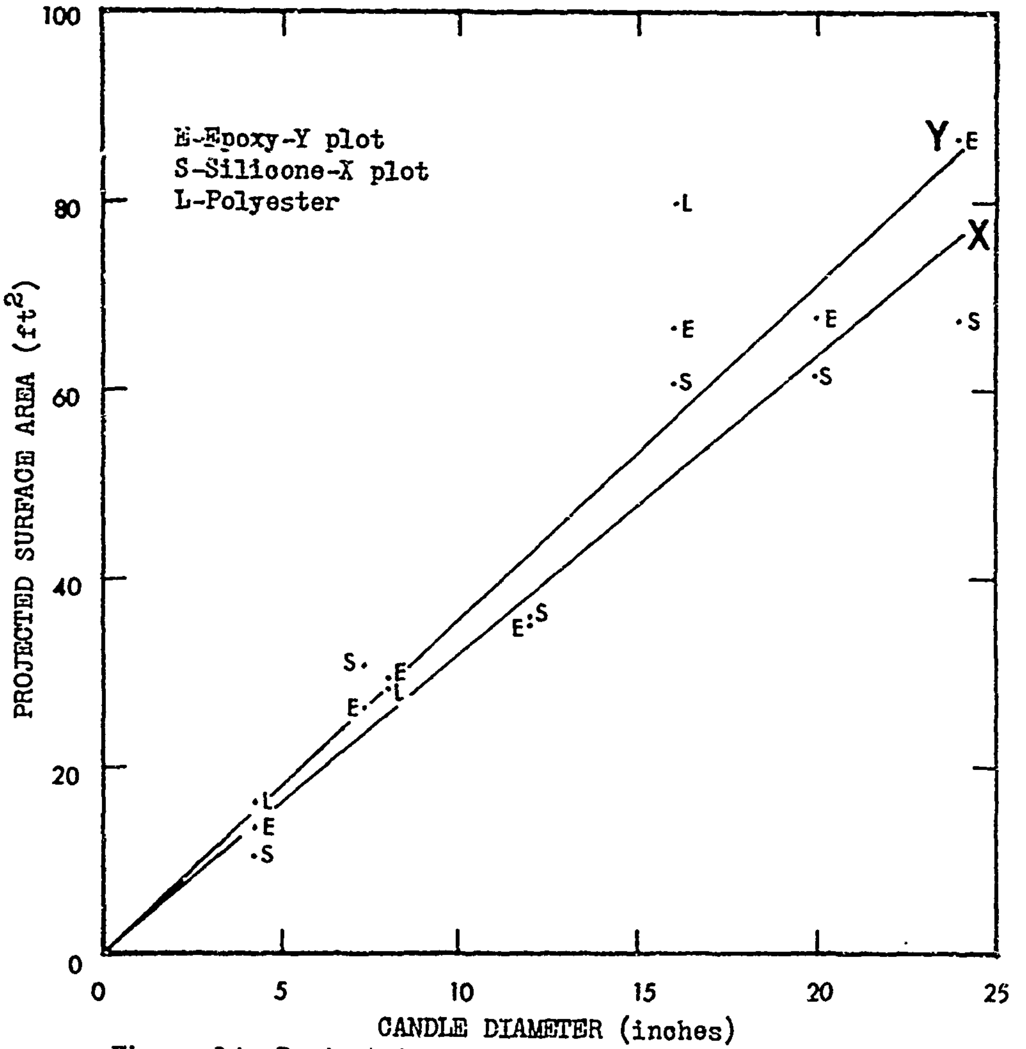

Figure 14: Projected surface area of the flame vs candle diameter for candles cast with different binder types. Shows candles with silicone binder generally have smaller flame from given size.

candles through 25 million candles. Clearly then, in this configuration the influence of the binder type seems to have been removed. The changeover from the non-linear function to one which appears to be linear may be an indication that an equilibrium condition has been achieved.

Experimental Uncertainties

As mentioned previously the values for the projected surface area of the flame are taken from movies of the flame image which has been projected by a parabolic mirror onto an easel. These values contain considerable variation due to differences in the type of film used, such as black and white versus color, variation in film development procedures, variability of the camera f-stop, smoke obscuring the flame, wind causing distortion of the flame, and the ability of the film reader to pick that frame which is representative of the entire burn, planimeter it and compare that value to the average luminous intensity for the flare. Clearly then there is ample opportunity for uncertainty in the presentation of these values.

When the program first started, the photographic data being collected was intended for use primarily to monitor the flame. When it was realized that the data being collected could be valuable for later evaluation in regard to the projected flame surface area, it was clear that some control over the methods would have to be placed in effect. From this point on, black and white film was always used, the lens opening was fixed at f5.6, and the same camera operating at 24 frames per second was used. Data plotted after these

adjustments were made seemed to form reasonable patterns. However, some of the data taken when colored film was used or when the camera lens stop was allowed to vary does not behave in a predictable manner. For example, in Figure 6 for the cast star cavity flares, candle MAPI 394 was taken with a variable f-stop and MAPI 463 was recorded on color film. Neither of these two data points fall in the region of expected behavior. In like manner in the silicone cast flare graph (curve S) of Appendix 8, candles MAPI 370, 371, 465 and 467 were recorded on color film and MAPI 393 was taken with an unknown lens opening. These data all deviate from the expected pattern. On the other hand, if these data are neglected the remaining data points form an effective brightness curve which appears reasonable.

Discussion of Flame Orientation

Another aspect of the study of flame size and shape is its orientation. In discussing the double star cavity flares (Part I), we pointed out the horizontal display of the flame from these units. The question naturally arises regarding the distribution of the light from such a flame.

In Figure 15, one can see the recorded luminous intensities at the location of each photocell. The high intensities in the 5 o'clock and 11 o'clock regions verify that the horizontally opposed flames were broadside to these regions. The flame tips were pointed toward 2 o'clock and 8 o'clock.

A particular feature of Figure 15 which is remarkable is that almost all regions directly below the flame give high intensities. This most desirable characteristic of the horizontally displayed flames is due to more efficient smoke removal from this region we can see a direct contrast to this in Figure 16 which shows the luminous intensities for each photocell for a 16-inch diameter solid cylindrical candle burned vertically with the flame pointed toward the ground. In Figure 16, the entire region directly below the flame is partially obscured by smoke as evidenced by the low intensity readings. Additional data of this nature for candles

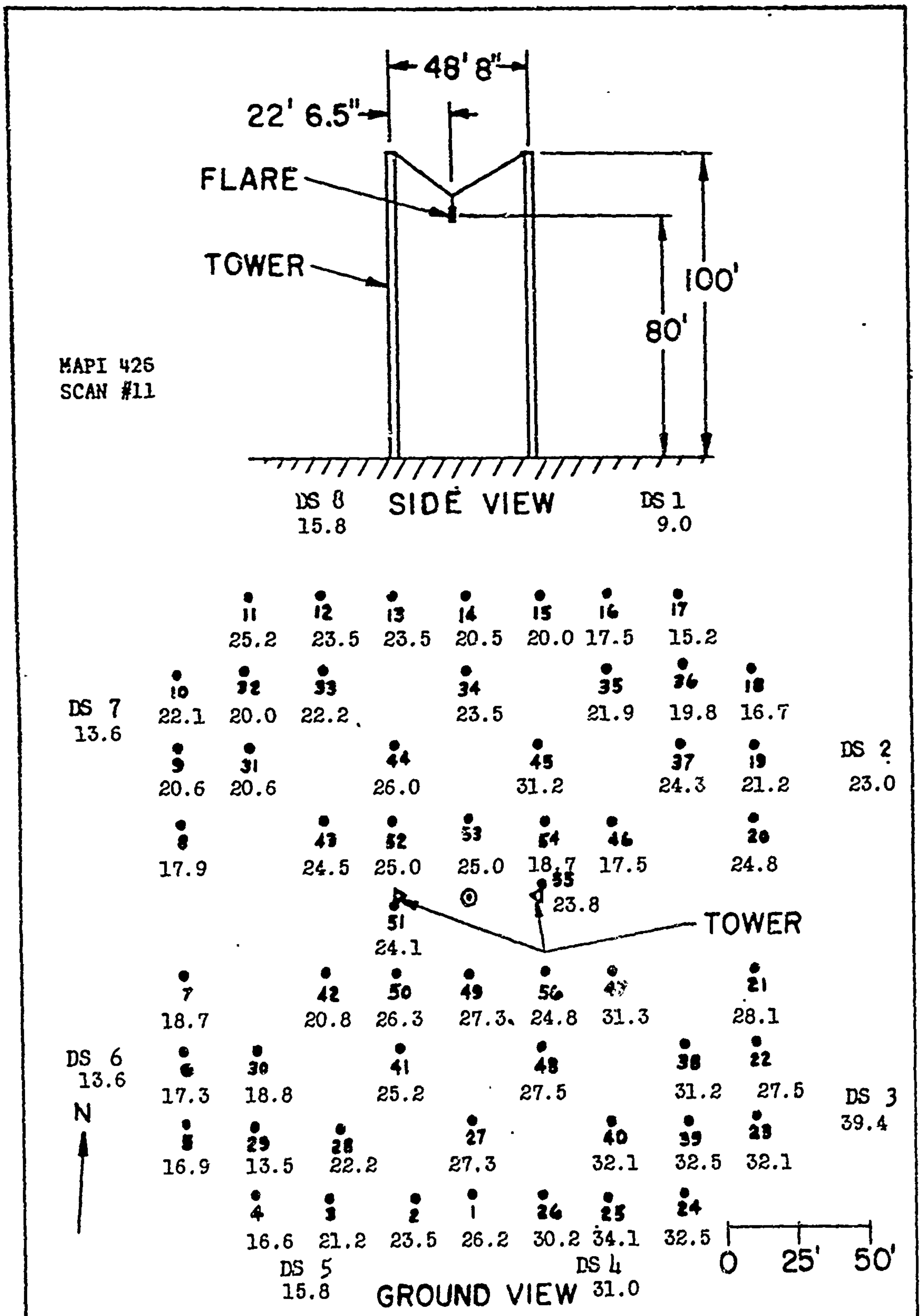

Figure 15: Luminous intensity ($x10^6$cd) by photocell at about 12th second into the burn of double star cavity candle MAPI 426.

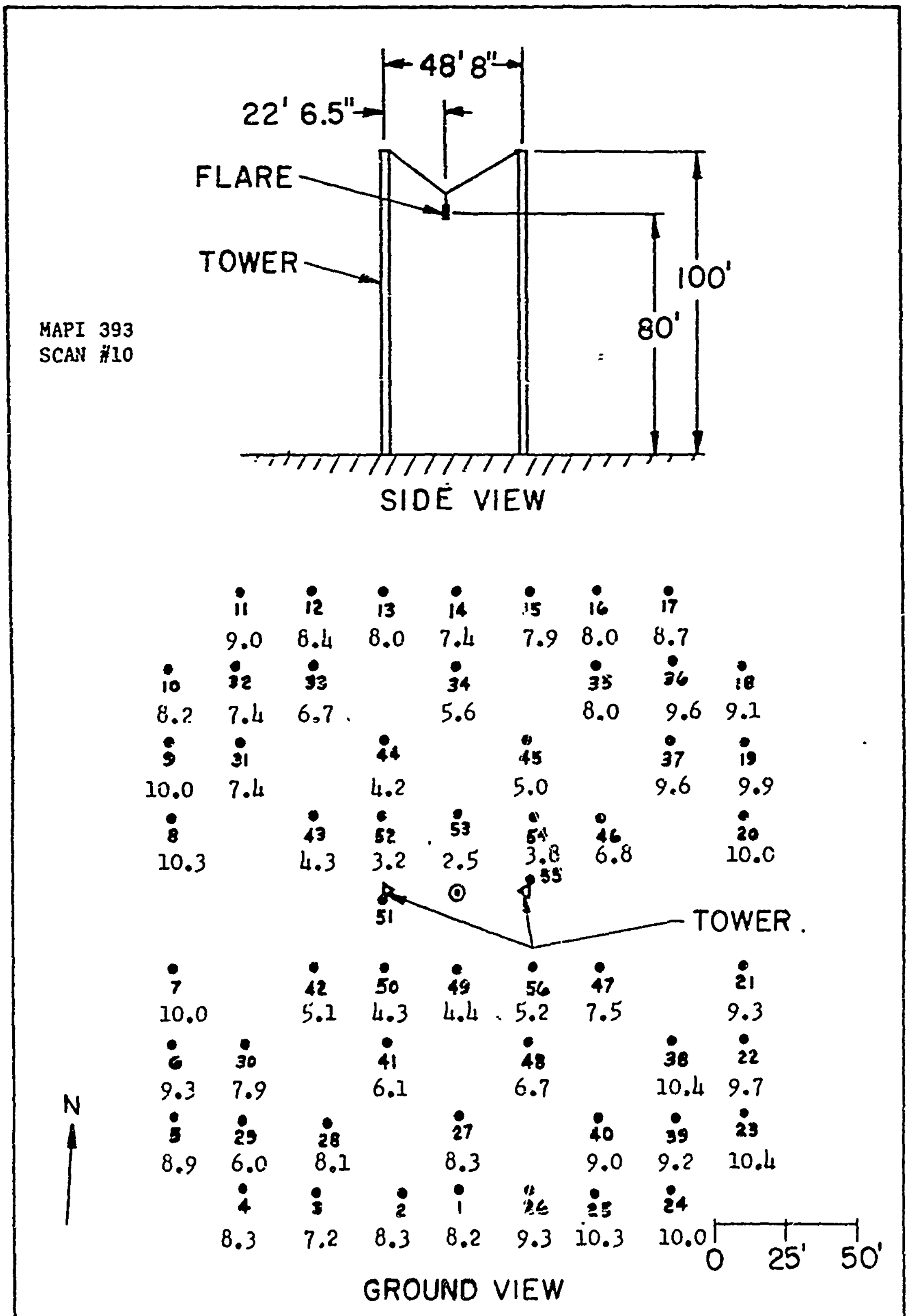

Figure 16: Luminous intensity ($x10^6$cd) by photocell at about 11th second into the burn of 16" diameter solid cylindrical candle MAPI 393.

MAPI 426 and 394 may be found in Appendix IX.

The flame orientation study is not complete. The limited data are presented here mainly to show the effect of smoke directly below a flame displayed vertically in contrast to the lack of smoke interference from a horizontal flame.

Conclusions

This part of the program provided several interesting results. One of the most amazing is that from a given candle diameter a small flame rather than a large flame is associated with high luminous efficiency. This observation is the exact opposite of what might have been expected. It was found also that the binder type has an overwhelming influence on the size of flame which is formed. It generally follows that the binder which produces the smallest flame is the best for making candles which radiate light with a high efficiency.

The foregoing statements apply to candles which are solid cylindrical end burning items with the flame in a vertical position and pointed toward the ground. In direct contrast to this orientation is the flame from the double star cavity candle which develops horizontally to the ground and is the result of combustion inside of a cavity. In units such as the latter the strong influence of the binder type which was present in the end burning candles seems to have been removed. This behavior points up the importance of candle shape and suggests how candle geometry can be used to transform an otherwise unacceptable binder system into a most useful one.

ACKNOWLEDGEMENTS

The author is indebted to many employees in the Air Force Armament Laboratory At Eglin Air Force Base, Florida, for their encouragement and support. Several members of the Illumination Branch of the Targets and Scorers Division contributed to this program. Although it is not possible to acknowledge all of them, it must be known that two persons made up the main core of the support. Mr. W. S. Cronk not only was instrumental in the initiation of the program but also frequently contributed ideas and provided guidance which proved to be most useful in the successful completion of this work. Mr. Larry Moran provided a stable point of contact and took care of the many administrative and technical details which needed attention as the program progressed.

At Crane, it also was the result of a team effort which made the task possible. Most of the work was accomplished within the Research and Development Department, whose many members supported the idea of casting flares most enthusiastically. The efforts and contributions made by several persons are especially noteworthy. The author wishes to acknowledge the work of Mr. Duane M. Johnson who set up and managed the early phases of the Diameter Studies, Mr. Donald Hazelton who planned and carried out most of the work during

the middle portion of the program, and Miss Brenda Sanders who patiently read most of the photographic data and kept track of the test data. Mr. Carroll Morrison did the artwork on the graphs for this report and Mr. Ralph Chipman contributed Appendix II. In the later months of the program, Mr. Robert Muessig and Mr. Gary Norris became associated with this work. Photometry and radiometry problems were handled by Mr. James Swinson.

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Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Naval Ammunition Depot Crane, Indiana 47522	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

25 MILLION CANDLE CAST FLARE DIAMETER AND BINDER STUDY VOLUME I

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Summary Report June 66 to June 67

5. AUTHOR(S) (Last name, first name, initial)

DOUDA, Bernard E.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1968		9

8a. CONTRACT OR GRANT NO. MIPR PG-6-58	9a. ORIGINATOR'S REPORT NUMBER(S) RDTR No. 105 VOLUME I
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Air Force Armament Laboratory Eglin Air Force Base, Eglin, Florida

13. ABSTRACT

The feasibility of making an illuminating candle which produces a luminous intensity of 25 million candles is demonstrated. The goal is achieved by igniting all surfaces of a star shaped cavity which is formed through the center of the candle.

The relationship between candle diameter and the ability of that candle to generate light efficiently is reported. A general degradation of efficiency is observed as the cast candle diameter increases from 4 inches to 24 inches.

Silicone, epoxy-polyglycol, polyester, polysulfide, epoxy-polyester, sodium perchlorate-methyl methacrylate, and various combinations of these binders are described as they are used to make candles for the diameter study, the binder study, and the 25 million candle flare.

Flame orientation and flame size effects are described. Contrary to common opinion, it is shown that a small flame size rather than a large flame from a given candle diameter is associated with candles which produce light with high efficiency. The binder is shown to be a major factor in the generation of various flame sizes and thus strongly influences the candle efficiency.

DD FORM 1 JAN 64 1473 0101-807-6800

Security Classification

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flares						
Illuminating Compositions						
Cast Flares						
Binder Study						
Epoxy Resins						
Methacrylates						
Perchlorates						
Sodium Nitrate						
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